Stones resting on the top soil cause heterogeneous patterns of fire-induced water repellency

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Introduction

The strength of fire-induced SWR depends mostly on temperatures reached during burning, the amount and type of litter consumed and pre-fire soil moisture level, the length of time these temperatures occur in the soil and soil properties. Water repellent soils can be difficult to model because of their extreme spatial and temporal variability.

It is known that stones resting on the soil surface can affect the thermal properties of soils. It has been demonstrated that, for dry soils, thermal conductivity and heat storage capacity increase with increasing stone content. Also, water percolation through water-repellent stony soils and implications for preferential flow have been studied by Urbanek and Shakesby (2009), who found that water infiltration is enhanced even through extremely water-repellent sand at large stone contents and suggested that the distribution and arrangement of stones in the soil body are critical for water flow. However, very little attention has been paid to the effect of stones resting on the soil surface in the development of SWR during burning. Stones on the soil surface may affect the distribution of heat during burning, and, consequently, may change the expected spatial distribution of SWR. During combustion of litter and above-ground biomass, the soil surface under stones is heated, reaching temperature peaks after a certain delay respect to areas not covered by stones (García-Moreno et al., 2013), increasing the time of residence of high temperatures. As a consequence, stones can change the expected spatial distribution of SWR. To date, very little research has concerned the effect of stones at the soil surface on the fire-induced pattern of SWR.

The objective of this research is to study the effect of stone cover and position of surface stones in the spatial pattern of SWR and soil infiltration capacity and soil infiltration capacity under different classes of fire severity (unburned, low, moderate and high fire severity).

Methods

STUDY AREA

In July 6th 2011, a wildfire caused by negligence affected 9,000 m^2 of shrubland and woodlands near Calañas (province of Huelva, southwestern Spain; Figure 1). The climate is Mediterranean, with cool, humid winters and warm, dry summers. The main vegetation types in unburned areas adjacent to the studied burned plots are herbs; shrubs are dominated by heaths (*Erica australis*), rockrose (*Cistus ladanifer* and *C. monspeliensis*) and brooms (*Genista hirsuta*, *G. triacanthos*, *Ulex parviflorus* and *Calicotome villosa*). Where present, tree species were *Pinus pinea* and *Eucalyptus globulus*.

EXPERIMENTAL DESIGN, SOIL SAMPLING AND LABORATORY ANALYSES

For the assessment of soil characeristics, four points were selected in unburned soils 20 m to the north, east, south and west of the fire-affected area. Four soil profiles were described and sampled for laboratory analysis and classification in plots 5 m from each point at coordinates randomly selected. Soil samples were transported in plastic bags, dried at laboratory room temperature (25 ºC) until a constant weight and sieved to eliminate coarse soil particles (> 2 mm). Soil acidity (pH), soil organic matter content and soil texture were determined in the laboratory.

Fire severity was assessed according to the criteria shown in Table 1. Areas showing homogeneous fire severity were divided into subareas with low stone (<20%) and high stone covers (>60%), as shown in Figure 2. The minimum size of the selected subareas was 10 m^2 and the minimum distance between adjacent areas was 4 m. SWR from selected subareas was studied during the first 7 days immediately following burning in randomly selected points. At each point, SWR was assessed in the soil area covered by the nearest stone (minimum diameter of 10 cm) and in the bare soil at the midpoint between this and the second nearest stone with maximum spacing of 20 cm (Figure 3). Prior to these assessments, ash and litter were gently brushed away where present.

SWR was determined by the water drop penetration time (WDPT) test. WDPT was classified according to Table 2, following the criteria suggested by Doerr (1998).

Table 1. Description of fire severity classes in the study area.

Fire severity	Description
Unburned	Not affected
Low	Burnt herbs; shrubs partly charred but not consumed and most branches intact after fire; < 50% canopy burned; occasional deposition of black ash; most soil organic layer unaffected
Moderate	Herbs completely consumed; stems thinner than 10 mm were not completely consumed; 50-80% canopy consumed; black and white ashes covering soil; organic layer deeply charred; white ashes covering part of the soil
High	Shrubs consumed and scorched trees; stems thinner than 10 mm were completely consumed (many shrubs were consumed completely except the base); white ash covering most of the soil surface; organic layer showing severe damages and litter consumed; mineral soil colour shows evidence of alteration

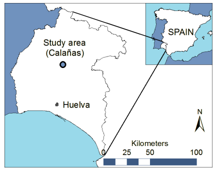


Figure 1. Study area.

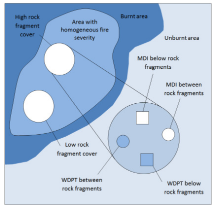


Figure 2. Experimental design. The number of determinations varied with the size of each sampling area, minimum distance between determinations was 1 m. In burned areas, minimum distance to unburned soil was 5 m.

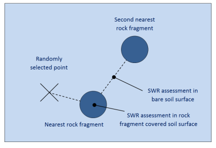


Figure 3. Assessment of soil water repellency (SWR). The minimum diameter of selected stones was 10 cm.

Results

SOIL CHARACTERISTICS

Soils were classified as Lithic Leptosols (IUSS Working Group WRB, 2006), showing an A-R profile, limited in depth by continuous rock within 10 cm of the soil surface. Soil characteristics are shown in Table 2.

Table 2. Soil characteristics. Mean ± standard deviation of soil depth, pH, organic matter content (OM), sand content, clay content and water content (percentage by weight) for each selected point (N = 4).

Depth (cm)	pH	OM (%)	Sand (%)	Clay (%)	Water content (%)
9.2 ± 0.8	5.7 ± 0.5	3.2 ± 1.2	50.2 ± 12.9	17.3 ± 5.7	2.10 ± 0.17

EFFECTS OF FIRE SEVERITY ON SOIL WATER REPELLENCY

WDPT from unburned soils and soils burned under different fire severities is shown in Table 3. Unburned soils in the study area are wettable, with WDPTs ranging between 0 and 3 s. In low-severity burned areas, WDPT was higher (median 5 s). No significant differences were found between WDPTs from unburned and low-severity burned sites. In contrast, SWR from moderate- and high-severity burned soils increased sharply from slight to strong WR.

The number of observations for different WDPT classes, fire severity and stone cover are shown in Figure 5. Most soil points were considered wettable in unburned and low-severity burned points (89 of 90 points). In moderate severity areas, soils were classified as wettable (32.5%), slightly (40.0%) and moderately water repellent (27.5%). In high-severity burned areas, all points showed WDPTs above 30 s, with soils classified as slightly (7.5%), moderately (30.0%) and strongly water repellent (62.5%).

Table 3. Median, mean, minimum and maximum water repellency (WDPT, s) for different fire severity classes. P-value from Kruskal-Wallis test is 0.0001. The same letters in column 4 (Mean WDPT) indicate no significant differences between groups.

Fire severity	N	Median WDPT	Mean WDPT	Minimum	Maximum
Unburned	40	2	2 a	0	3
Low	40	5	9 a	0	35
Moderate	40	41	44 b	6	96
High	40	203	232 c	40	561
All groups	160	20	72	0	561

EFFECTS OF STONES ON SOIL WATER REPELLENCY

Table 4 shows the results of the Mann-Whitney U test for WDPT from areas with different fire severity and stone cover class in bare and stone covered areas. In stone covered areas, no significant differences were observed for WDPT between high and low stone cover areas under different fire severities. In bare areas, no significant differences were observed between low (<20%) and high stone cover (>60%) in unburned soils and soils affected by low-severity burning. Significant differences were found between mean WDPT from bare areas points under different stone cover classes in moderate- and high-severity burned areas. In moderate-severity burned areas, the median value of WDPT increased significantly from 24 s in low stone cover areas to 47 s in high stone cover areas (p=0.0100). In high-severity burned areas, the median value of WDPT increased significantly from 91 s in low stone cover areas to 270 s in high stone cover areas (p=0.0006).

In control unburned areas, no significant differences were observed between WDPT values from bare and stone covered areas with a low or high stone cover classes. In contrast, in burned areas, SWR was increased significantly from bare to covered areas. In areas affected by high severity burning and high stone cover (>60%), no significant differences were found in SWR from bare to covered areas, although median WDPTs were 270 and 304 s, respectively. Figure 4 shows the distribution of WDPT classes for different fire severity and stone cover class.

Table 4. Results of the Mann-Whitney U test for WDPT (median; range between brackets) from areas with different fire severity, stone cover class and type of determination (bare and stone covered areas).

Fire severity	Stone cover	WDPT from bare areas (s)	WDPT from stone covered areas (s)	p
Unburned	<20%	2 (0, 3)	3 (0, 3)	> 0.5
	>60%	2 (0, 3)	1 (0, 3)	> 0.5
	p	> 0.05	> 0.05	
Low	<20%	3 (0, 5)	13 (3, 25)	**0.0010**
	>60%	3 (1, 7)	19 (6, 35)	**0.0003**
	p	> 0.05	> 0.05	
Moderate	<20%	24 (6, 43)	64 (30, 74)	**0.0007**
	>60%	47 (19, 69)	49 (15, 96)	>0.05
	p	**0.0100**	> 0.05	
High	<20%	91 (40, 197)	218 (120, 407)	**0.0010**
	>60%	270 (147, 363)	304 (117, 561)	> 0.05
	p	**0.0006**	>0.05	

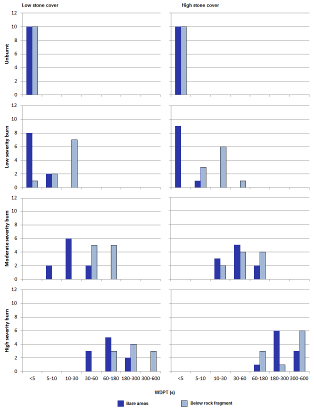


Figure 6. Number of WDPT data for different classes (<5, 5-10, 10-30, 30-60, 60-180, 180-300 and 300-600 s), fire severity and stone cover class (low, <20%; high, >60%).

Discussion

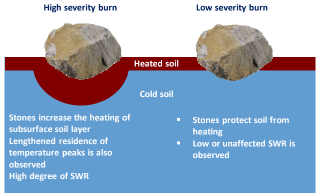
SWR increased with fire severity. This agrees with DeBano et al. (2000), who reported that SWR increases with burn severity (although it is expected that water repellency would disappear after extreme severity burning). Severity of fire effects on soils is conditioned by temperature peaks and heating duration in soil. According to DeBano and Krammes (1966), the intensity of fire-induced SWR depends for the most part on temperatures reached during burning. Fire-induced SWR appears when temperatures of 175 – 200 ºC are reached, while it is destroyed at temperatures of at least 350-400 ºC (Chandler et al., 1983; Doerr et al., 2000). After different wildfires in Mexican volcanic highlands, Jordán et al. (2011) found that moderate-severity burning increased SWR, but high-severity burning either enhanced or destroyed hydrophobicity, as different temperature peaks or heating periods were reached at the soil surface. High WDPTs observed in our research may be explained by temperature peaks surpassing the threshold for water repellency development.

EFFECTS OF STONES ON FIRE-INDUCED SOIL WATER REPELLENCY

After fire, litter and aerial plant parts are partly or completely consumed, and the mineral soil surface may be partly exposed or covered with varying amount of ash, charred litter and plant residues and surface stones (García-Moreno et al., 2013). Only in recent years, however, have some authors highlighted the role played by materials resting on the soil surface (such as ash and charred litter) in the immediate post-fire period. In Mediterranean soils, several authors have reported changes in the surface soil hydrology and water repellency as a consequence of charred litter and ash layers (Bodí et al., 2011; Bodí et al., 2012; Cerdà and Doerr, 2008; Zavala et al. 2009). However, these are short-timed effects, as charred litter and ashes may be rapidly removed or redistributed by wind and runoff.

In fire-affected stony soils, changes in SWR at the soil surface may alter this response. Shakesby et al. (2003) suggested that spatial heterogeneity of SWR after high-severity burning is comparatively common in Mediteranean soils, with implications for runoff generation and erosion processes. In this research, stones resting on the soil surface are responsible for a patchy distribution of SWR and infiltration after burning. Even after low-severity burning with a low stone cover (<20%), SWR was enhanced at the soil surface directly beneath stones. This effect may be explained by the heat flow dynamics between fire, stones and the soil surface. Our results show a strong difference in water repellency between bare and stone-covered soil after moderate- and high-severity burning. It is suggested that prolonged heat transfer from stones to soil lengthened the period of residence for temperatures above the threshold for water repellency induced at the soil surface, hence increasing WDPT (Figure 7). In bare areas, weaker water repellency was induced. In these cases, temperatures during the fire at the soil surface may have been even higher, but more short-timed peaks were probably reached during low-severity burning.

After moderate- and high-severity burning, no significant differences were observed between WDPTs from bare and covered sites under a high stone cover, probably as a consequence of the proximity between stone-covered areas and high fire temperatures: stones can induce a lateral heat flow (Poesen and Lavee, 1994), which may have reduced the intensity of the temperature gradient between the bare area between nearby stones and covered sites (Figure 8). Also, authors have observed occasional amounts of ash between neighbouring stones, as a result of prolonged combustion of litter and plant residues with low oxygen availability. Flameless smouldering may have contributed to enhanced water repellency in bare sites with a high stone cover.


High severity burn

Low severity burn

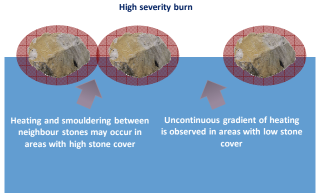
Heated soil

Cold soil

Stones increase the heating of subsurface soil layer
Lengthened residence of temperature peaks is also observed
High degree of SWR

- Stones protect soil from heating
- Low or unaffected SWR is observed

Figure 7.


High severity burn

Heating and smouldering between neighbour stones may occur in areas with high stone cover

Uncontinuous gradient of heating is observed in areas with low stone cover

Figure 8.

Conclusions

The effect of stones resting on the soil surface on the development of water repellency in fire affected soils has been studied in this experiment. After a wildfire, it was observed that burning induced water repellency in previously wettable soils. The degree of repellency increased with burning severity.

stones resting on the soil surface may cause heterogeneity in the spatial distribution of water repellency after burning. In areas with a low stone cover (<20%), water repellency from soil surfaces covered by stones increased relative to soil surfaces not covered by stones, with the mean WDPT being more than 3 times higher.

In areas with a high stone cover (>60%), SWR was significantly higher for bare soil surfaces compared with stone covered soil surfaces after low-severity burning. In moderate- and high-severity burned soils with a high stone cover, mean WDPTs were higher than in soil surfaces not covered by stones, but no significant differences were observed. In this case, the proximity of stones during severe burning may have contributed to reducing the intensity of the temperature gradient between bare and covered sites. Smouldering processes after the passage of fire are also suggested as a factor implied in water repellency development.

ACKNOWLEDGEMENTS

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